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Climate change and the transition to a low carbon economy – Carbon targets and the carbon budget

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ABSTRACT

Carbon intensive fuels generate a significant negative externality which is quite relevant for climate change mitigation policy. We propose a dynamic growth model where output is produced using two types of energy sources: fossil fuel and renewable energy. Fossil fuel discovery, extraction, and associated costs are incorporated in our model together with the dynamics of greenhouse gas emissions and consequent damages. Consistent with the empirical facts, our numerical solutions suggest that fossil fuels, especially coal, should not be exploited to depletion. Furthermore, renewable energy should be gradually phased in to meet targets consistent with the Paris 2015 agreement. We show that adopting those policies should slow down the growth rate of cumulative emissions; but the outcome is contingent upon the carbon emission targets set for advanced countries, as distinct from those assigned to developing countries.

1. Introduction

In its numerous reports, the International Panel on Climate Change (IPCC) (2016) has stated that global temperatures, as compared to the pre-industrialization period, have risen roughly 0.8 °C. Yet, in contrast to this slowly-moving temperature trend, the incidence of weather extremes and climate disasters has significantly increased in terms of frequency and severity.[2]

The Paris agreement of December 2015 is aimed at restricting world temperature rise to 2 °C and, if possible, remaining below 1.5 °C. This has brought a series of pressing issues to the center of international debate. These include questions like how close we are to the carbon budget, what should be done to stay below dangerous thresholds, how should each type of fossil fuel be reduced, what amount of fossil fuel each country or region should leave in the earth, and how should the production of renewable energy be accelerated to replace fossil fuels in the near term?

Recent research shows that there is a limited amount of carbon that the atmosphere of the earth can absorb (carbon budget) without producing further dangerous trends in global warming (Edenhofer et al., 2014; Jakob and Hilaire, 2015). If this carbon budget is exceeded, one overshoots an important tipping point. Overwhelmingly, the origination of carbon emissions is fossil fuel, e.g., coal, oil, and natural gas. Much is known about consumption trends for each of the fossil fuels and what their emission intensity is.

In this paper, we predominantly focus on coal. Coal represents almost one third of the global primary energy supply and generates the greatest emissions. It also has the largest reserves and thus, when measured by the reserve-to-production ratio, the longest time-to-exhaustion. Yet, many countries around the globe continue extensive coal mining operations. The crucial role of coal for climate change is discussed in Eichner and Pethig (2017) and Sartor (2018).

As climate scientists warn us, the possibility of crossing the carbon budget is imminent. Yet, there might be a need to define different carbon budgets, expressing different target levels for advanced and developing countries. In this paper, we show that this is particularly important for developing fossil fuel-dependent countries; these are countries where emissions from coal combustion have risen significantly and the transition to a low carbon economy is slow.

Overall, the production of fossil fuels of all types has risen globally since the early 1970s. Coal production surged in top producing countries, e.g., China, followed by the United States, India, and Australia. Growth of world coal consumption has also shown a significant increase. However,

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[2] See International Monetary Fund (IMF) (2017) and Mittnik et al. (2018).

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in some regions, fossil fuel consumption's share in total energy shows a substantial decline, notably in North America, the EU, and in OECD countries, mostly because of the increased use of clean energy. Although almost two-thirds of electricity in the United States comes from fossil fuels, the trend has been declining. On the other hand, coal consumption has been rising in many developing countries, particularly in Asia and in Latin America, reflecting their dependence on it for electricity. Several studies have suggested that substantial fossil fuel should remain underground. According to McGlade and Ekins (2015), fossil energy reserves that contain massive carbon (around 11,000 Gt CO_2) drastically exceed the carbon budget suggested by the IPCC[3] for the period of 2011–2050. There are a wide range of estimates on the amount needed to stay within the carbon budget and to maintain global warming rise of less than 2 °C, as compared to pre-industrial averages. Based on the calculated effects of coal emissions, they argue that most coal reserves should be left underground, especially in the United States and Australia. In a study of the optimal extraction of fossil fuel and global warming, Hoel and Kverndokk (1996) state that extraction rates should be slower when there is a greenhouse effect, which there is. Another estimate, maybe even a more reliable one, is the International Panel on Climate Change (IPCC) (2018) finding that unless net emissions go to zero by the year 2040, atmospheric CO_2 concentration will not remain constant from then on.[4]

Compared to previous research by van der Ploeg and Withagen (2011) and Greiner et al. (2014), our contribution includes an analysis of the economics of the discovery and extraction of coal reserves, with an emphasis on reserves and costs associated with the extraction. In addition, we use a production function where capital stock creates clean energy, and goods are produced using two types of energy sources. Here, our primary focus is on coal and renewable energy. We also study damages from greenhouse gas (GHG) emissions caused by the usage of coal. This generic model is then specified as two model variants, which are suggested by a recent study supporting such an approach (see Carbon Pricing Leadership Coalition (CPLC), 2017). This report considers different cumulative emissions as well as GHGs emission targets for advanced countries (ACs) and developing countries (DCs). Our contribution is that we study different targets of carbon emissions characterizing different environments. ACs' targets need to be lower since their cumulative contribution to pollution is already much higher. In contrast, Carbon Pricing Leadership Coalition (CPLC) (2017) argues that DCs need to be allowed more flexible (higher) carbon goals since their industrialization and development, together with demand for fossil fuels, occurred much later than for ACs and their share of total emission is lower. In fact, the current climate negotiations seem to converge toward the view that the ACs – as the main cumulative polluters – need to have lower future pollution targets than the DCs which also need to obtain greater financial support and help in their mitigation efforts (see Carbon Pricing Leadership Coalition (CPLC), 2017).[5]

To examine the relationship between fossil fuel resources and their externality effects in different types of economies and environments, our proposed model is solved using Nonlinear Model Predictive Control (NMPC).[6] This demonstrates optimal paths for stocks of fossil fuel and accumulated past extraction, capital accumulation, and their effects on pollution with a dynamic path for GHG emissions. Optimal paths for fossil fuel resources in this paper show an inverted U-shape with an eventual decline that either leads to a certain constant level or a complete depletion. This occurs when there are few discovered fossil fuel resources, and where a further fossil fuel discovery would increase the extraction rate. Eventually, as the results illustrate, the extraction rate will fall. The depletion of the fossil fuel reserve occurs in the absence of alternative sources of energy, e.g., green or clean energy, as discussed in Nyambuu and Semmler (2014) and Nyambuu et al. (2014). In this paper, we show that fossil fuel does not have to be completely extracted if renewable energy is available and phased in gradually. How much fossil fuel may be left in the ground depends on the discovery rate and the initially available reserves. In such a case, the damages and negative externality of fossil fuel can be limited. We emphasize the importance of the substitution effect of fossil fuel by green energy as measured in our model by an efficiency index.

The paper is organized as follows: Section 1 is introductory; Section 2 provides a literature review; Section 3 illustrates some stylized facts on fossil fuel reserves, time-to-exhaustion, carbon intensity, and carbon dioxide (CO_2) emissions; Section 4 proposes a dynamic model with discovery and extraction of fossil fuel, and damages resulting from CO_2 (GHG) emissions; Section 5 uses NMPC to study the extent to which fossil fuel can be replaced by renewable energy for two model variants; Section 6 concludes the paper.

2. Literature review

2.1. Models with resource extraction

There was early literature on growth and resources extraction. Examples where a single resource is used as one of the production factors can be found in Solow (1973), Stiglitz (1974), and Dasgupta and Heal (1974), who all considered an extraction rate and a flow of resources. In other papers, such as those by Hotelling (1931) and Solow (1974), the extraction of non-renewable resources and their scarcity are discussed; in these papers, the long-run extraction costs and price movements in competitive markets are studied. However, as Livernois (2009) argued, the early Hotelling model was oversimplified, assuming a perfectly competitive market and failing to take discovery and extraction costs into account. Using an intertemporal model with a monopolistic producer who makes a decision on optimal extraction of exhaustible resources, Nyambuu and Semmler (2014) show the dynamic evolution of discovery rates,[7] proved reserves,[8,9] and extraction rates. Their numerical solution, solved by NMPC, for the extraction rate demonstrates different patterns depending on the initial stock of the proved reserves. An inverted U-shaped pattern is observed – extraction rates are high when there are large undiscovered resources and new discoveries are obtained, whereas extraction rates decline with diminishing resources and lower discovery rates. Long-run trends are discussed in studies by Pindyck (1978), Slade (1982), Liu and Sutinen (1982), Livernois and Uhler (1987), Cairns and

[3] A more hesitant statement on atmospheric GHG concentrations is made by Gray (1998). In this context, see also Ritchie and Dowlatabadi (2017) and Höök and Tang (2013) on assumptions pertaining to the future usage of fossil fuel and emission scenarios.

[4] In this context, it is interesting to note that long-run estimations up to 2040 by the International Energy Agency (International Energy Agency (IEA), 2016a) demonstrate much lower overall primary energy demand, especially for coal, under the proposed constrained carbon budget.

[5] Of course, we note that new technology might help DCs to bring their targets down.

[6] See Grüne and Pannek (2011), Grüne et al. (2015), and Nyambuu and Semmler (2017) for the details on the NMPC procedure.

[7] In this paper, we follow the discovery rate described in Nyambuu and Semmler (2014, p. 272) where "a further discovery of the undiscovered part of the resource will increase the stock of the proved reserves, which can be extracted."

[8] According to the U.S. Energy Information Administration (EIA), estimated proved reserves are "volumes of hydrocarbon resources that analysis of geologic and engineering data demonstrates with reasonable certainty are recoverable under existing economic and operating conditions." (available at https://www.eia.gov/naturalgas/crudeoilreserves/).

[9] For the global peak analysis based on oil discovery data, instead of proved oil reserves or 1P data, Bentley et al. (2007) suggests the use of "proved + probable" or 2P data. Oil production projections, together with their revisions and the availability of fossil fuels, are reviewed in Wachtmeister et al. (2018). They also emphasize new technology, especially in developing scenarios. New technology has been developed and applied to the production of fossil fuel at a very fast rate.

Van Quyen (1998), and Greiner et al. (2012).

2.2. Modeling environmental damage

Growth models have also been extended to study the effects of climate change, usually focusing on social, economic, and environmental damages, arising from CO_2 (GHG) emissions and from changes in temperature. The starting point for this type of modeling is the collection of integrated assessment models developed by Nordhaus (2008). These days, much research focuses on the substitution of fossil fuel with renewable energy. For example, Edenhofer et al. (2014, p. 476) study long term implications of climate change mitigation consistent with sustainable development. Along this line, they argue that "the limiting factor of global energy supply is not the scarcity of fossil fuels, but rather the limited disposal space of the atmosphere implied by climate stabilization targets."

In the modeling of environmental externalities within economic growth, in addition to consumption, Byrne (1997) used a pollution stock in the utility function of a representative agent. Similarly, environmental quality in terms of net pollution was incorporated in the social welfare function in Smulders and Gradus (1996). Extensions to the welfare function using damage costs were introduced in papers such as Greiner (2011), and Greiner et al. (2014). Toll (2015, pp. 298–299) provides a comprehensive empirical study on consequences that climate change may have on welfare. He uses estimates of the social cost of carbon that compare future discounted damage costs with resource use today. There are, however, uneven effects for regions and countries. For example, there is a higher vulnerability to damages from climate in low-income countries. Thus, the social cost of climate change comes with large uncertainties and an uneven distribution, see Mittnik et al. (2018).

Drivers of the CO_2 emissions, as defined in Steckel et al. (2015), include energy use and carbon intensity for certain types of energy. While Greiner et al. (2014) elaborate on generic causes of changes in GHG emissions, Bondarev et al. (2013) consider more specific variables, e.g., technological efficiency affecting the concentration of GHG in the atmosphere. These models introduce variables such as emissions' intensity, atmospheric recovery, an increase in temperature from pre-industrial levels, and the abatement rate. Other studies, e.g., by Bauer et al. (2013) and McCollum et al. (2014), analyze fossil fuel markets in the long run and discuss how climate stabilization and climate change mitigation can be achieved by constraining fossil fuel consumption.

2.3. Technology

Recent literature is often concerned with new technologies that support the transition to a low carbon economy. A number of studies, including Edenhofer et al. (2006), Heinzel and Winkler (2011), van der Ploeg and Withagen (2011), Acemoglu et al. (2012), and Greiner et al. (2014), extensively covered this issue. For example, Acemoglu et al. (2012) use two types of technologies - "dirty" and "clean"- in their production models. They argue that "when inputs are sufficiently substitutable, sustainable growth can be achieved with temporary taxes/subsidies that redirect innovation toward clean inputs" (Acemoglu et al., 2012, p. 131). When production factors are highly substitutable, they found that an "immediate switch of R&D resources to clean technology, followed by a gradual switch of all production to clean inputs" is required (Acemoglu et al., 2012, p. 159). Using U.S. energy sector data, the transition to clean technology is discussed in Acemoglu et al. (2016). Capital is used in the production of the renewable energy in some cases, while in others it is not required, e.g., in van der Ploeg and Withagen (2011). They also examine the optimal transition date, optimal usage of polluting and non-polluting energy sources, and discuss whether or not it is wise to extract all the exhaustible resources.

Yet, the replacement of carbon-intensive energy, e.g., coal by renewables, at a large scale and at faster rates, can be quite challenging.,[10],[11] Besides support from the private sector, this process largely relies on changes in governmental policies in terms of both demand-side and supply-side measures, and enforced targets. Yet, overall, as Popp (2015) discusses, new technologies can also help DCs bring down their GHG emissions and reduce coal consumption.

3. Stylized facts

In order to provide some empirical background for our approach in the next section, we present some statistics and facts on the historical development and on current trends related to fossil fuels, coal in particular. These include fossil fuel reserves, time until exhaustion, energy investments, carbon intensity, and CO_2 emissions in advanced and developing countries.

3.1. Fossil fuel reserves and time to exhaustion

Proved reserves[12] as well as the reserve-to-production (R/P) ratios for different types of fossil fuels, including coal and oil, are shown in Fig. 1 and based on British Petroleum (BP) data. The length of time to exhaustion is shown with R/P ratios. According to BP (2017), global coal proved reserves amount to 1.1 trillion tons at the end of 2016 and it would last 153 years at current levels of production. Many coal-rich countries have high R/P ratios: Russia (417 years) and the United States (381 years), followed by others. Despite its massive coal reserves, China has only 72 years of coal due to its large coal consumption, particularly as compared to other countries.

Given the large coal reserves and coal's reserve-to-production ratio, one can conclude that the temptation to use coal as a transition energy to a less carbon-intensive economy is likely to create serious problems if one's goal is to keep the carbon budget below the Paris Agreement (a temperature rise of $<2\,^{\circ}$C and efforts to achieve a rise of $<1.5\,^{\circ}$C above preindustrial levels).[13] Instead, a substitution for coal using gas has been considered by major countries. According to the U.S. Energy Information Administration (EIA), there has been a significant expansion in the production of gas[14] for use as a major energy source and a corresponding decline in coal. We also note that coal production came under competitive pressure from shale gas, at least while the gas industry was expanding.

Projections by International Energy Agency (IEA) (2017) up to year 2040 indicate an exponential growth of 80% in the output of inexpensive shale gas which would contribute to the transition to the low-carbon economy.[15] Growing investment in clean energy supports this effort as well. According to International Energy Agency (IEA) (2017, 2018) and BloombergNEF (2018), total worldwide energy investments increased,

[10] Natural gas is an important transition energy source. For more details, see Hultman et al. (2011), Levi (2013), and Gevorkyan and Semmler (2016). In our paper, we focus on coal because of the reasons discussed above and summarized at the end of section 3.2.

[11] A substitution between fossil fuel and renewable energy in the modeling of economic growth is discussed in several papers including Barreto (2018) and Erikson (2018).

[12] BP methodology on proved reserves data states that it is "generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and geological conditions." (available at https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/oil/oil-reserves.html).

[13] For a recent study on this issue, see International Panel on Climate Change (IPCC) (2018).

[14] For details on the shale energy sector, see Gevorkyan and Semmler (2016).

[15] US shale gas revolution is discussed in Fukui et al. (2017) presenting experience curves that describe a relationship between the gas price and its output.

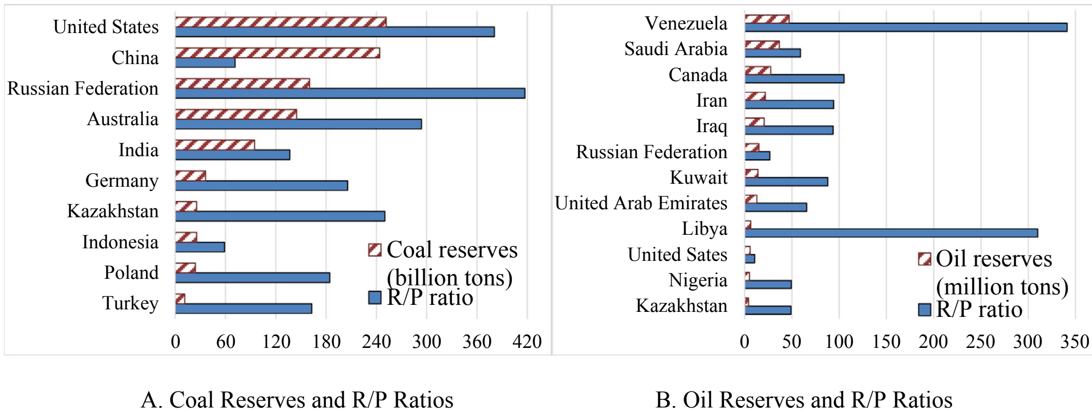


Fig. 1. Fossil Fuel Reserves and Reserve to Production (R/P) Ratios. Panel A of the figure shows total proved reserves of coal in billion tons and R/P ratios expressed in number of years for different countries (at the end of 2016). Panel B demonstrates oil reserves in million tons and R/P ratios in number of years. Data source: Constructed using data from British Petroleum (BP) Statistical Review of World Energy (2017).

with additional expansion in renewables, through the early 2010s. While investments in clean energy remained at a high level, fossil fuel investments started dropping in 2015. Downward trends in clean energy production costs since 2000 have contributed to higher investments into clean energy (see International Energy Agency (IEA) 2018). We also observe a shift in the rise in clean energy investments away from Europe toward Asia, mainly in China (see International Energy Agency (IEA), 2018 and BloombergNEF, 2018).[16] With respect to energy efficiency, there was a significant gain, especially in Europe (see International Energy Agency (IEA), 2018).

3.2. CO_2 emissions and carbon intensity

Following the industrial development of the late 1980s, developing countries' CO_2 emissions have risen (see Fig. 2a).[17] In addition, a comparison of average CO_2 emissions per capita between 1960 and 2014 indicates that countries with large population, e.g., China and India, have much lower emissions per capita (see Fig. 2b). While the emission from coal combustion has fallen in many countries due to lower coal consumption and higher renewable energy usage, it has increased in some other countries, especially in China, since the late 1990s. High economic growth in certain developing countries was achieved at great environmental cost. Major contributions came from electricity and heat generation, accounting for around 40% (see International Energy Agency (IEA), 2016b). According to an estimation by Boden et al. (2017), global carbon emissions from burning fossil fuels stood at 9.9 billion metric tons in 2014. Because of their high carbon intensity,[18] coal and oil accounted for around 45% and 35% of global emissions respectively, while natural gas contributed only 20%.

As shown in this section, coal has the greatest CO_2 emissions among the fossil fuels and exhibits the greatest reserves with the longest time to exhaustion, and it remains the preferred source of energy in many developing nations. Since fossil energy moves us toward the critical boundaries of the carbon budget, our model focuses primarily on some features of fossil fuel as a source of energy, as well as its alternative, renewable energy.

The above historical emission data helps us to understand general trends as well as to observe related specifics for both advanced and developing countries.

4. A dynamic growth model

We present a growth model that is based on two types of energy inputs: fossil fuel (q_t) and renewable energy, the latter created through the use of capital. Similar models have been introduced by others, e.g., Byrne (1997), Smulders and Gradus (1996), Greiner (2011), van der Ploeg and Withagen (2011), and Greiner et al. (2014). In order to avoid different types of capital, we simply assume that there is renewable energy capital stock (K_t) that generates, with some efficiency, clean energy. Such a generic model will be introduced next, followed by different model variants specified and calibrated for two regions of the world; for advanced countries (ACs) and for developing countries (DCs); these are represented by different parameter constellations, parameter dependent solutions of the model, and different targets.

The generic model can be sketched as follows. Output (Y) can be produced by the following static equation, where efficiency indices for K and q are E_1 and E_2, respectively:

$$Y = E(E_1 K + E_2 q)^{\sigma}, 0 < \sigma \leq 1, E > 0 \tag{1}$$

A greater efficiency index for capital, E_1, means a greater transformation of abundantly available energy, such as sun, water, and wind, into renewable energy used in production, transportation, heating and so on.[19] Similarly, a greater efficiency index for fossil fuel, E_2, represents a more efficient transformation of fossil fuel, q, into outputs. These efficiency parameters will play an important role in our model variants.

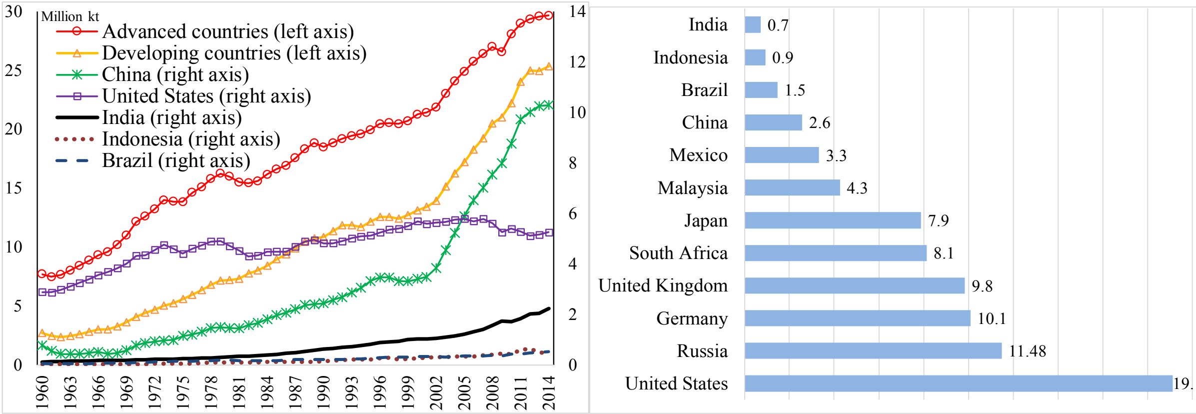
On the other hand, as discussed above, the amount of recoverable resource, e.g., fossil fuel, is a dynamic process. Incorporating the discovery of undiscovered fossil fuel is imbedded in a dynamic equation. The discovery is determined by three variables: the initial total available fossil fuel (R^0), accumulated past fossil fuel extraction (y), and the value of the fossil fuel reserves below which no new deposits will be discovered

[16] Renewables represented 33% of world investment in China in 2017, whereas Europe and the US garnered only 22% and 14% respectively (see International Energy Agency (IEA), 2018 for details).

[17] Territorial emission has challenges. Peters et al. (2011, p. 8903) addressed this issue and their results show that "net emission transfers via international trade from developing to developed countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008".

[18] IPCC Guidelines (2006) indicate carbon emission factors for gas (15.3 tC/TJ), oil (15.7–26.6 tC/TJ), and primary coal (25.8–29.1 tC/TJ).

[19] We admit that there are also input constraints for the production of renewable energy. See, e.g., the work by Elshkaki and Graedel (2013) for different technology for generating electricity and metals requirements, Habib and Wenzel (2014) write on supply constraints and risk, and Tokimatsu et al. (2017, 2018) on metal requirements in the modeling of energy. However, fewer constraints are seen in Jha (2017). Yet of course such constraints would affect the efficiency parameters.



A. CO_2 Emissions B. Average CO_2 Emissions tons per capita (1960-2014)

Fig. 2. CO_2 Emissions. Panel A demonstrates CO_2 emissions in million-kiloton (kt) for advanced, developing, and other countries. Panel B shows average amount of CO_2 emissions per capita expressed in tons between 1960 and 2014 for advanced and developing countries. Data source: Constructed using data from the World Bank World Development Indicators.

(R^z). This can be described as a function of $f(R^0 - y - R)$ or more specifically $\alpha(R^0 - y - R - R^z)$.[20]

In addition, we also account for the cost associated with the exploitation of the fossil fuel as shown as $C(R^0 - y)$ or specify it as $\phi(R^0 - y)^{-2}$. We should note that the rise in the exploitation cost is related to the declining stock of the fossil fuel. The cost of extraction becomes more expensive especially when a large part of the fossil fuel is discovered and exploited.

The following welfare function with consumption (C) and damages from CO_2 emissions $(-\nu(D - D^*)^2)$, arising from the cumulative CO_2 emissions, D, is used with control variables of consumption (C) and fossil fuel extraction rate (q). The household's welfare is constrained by the dynamics of the state variables: capital stock (K), stock of fossil fuel (R), accumulated fossil fuel extraction in the past (y), and damages resulting from GHG emissions (cumulative) (D) caused by the usage of fossil fuel.[21]

$$\max_{C,q} \int_0^\infty e^{-\theta t}\left(\ln(C) - \nu\left(D - D^*\right)^2\right)dt \tag{2}$$

Subject to

$$\dot{K} = Y - C - \delta K - \phi\left(R^0 - y\right)^{-2} q \tag{3}$$

$$\dot{R} = \alpha\left(R^0 - y - R - R^z\right) - q \tag{4}$$

$$\dot{y} = q \tag{5}$$

$$\dot{D} = \psi q - \rho\left(D - \xi D^*\right) \tag{6}$$

where D^* denotes the pre-industrial level of CO_2 emission (GHG) caused by fossil fuel, ρstands for GHGs' atmospheric lifetime with $0 < \rho < 1$, ξ affects the target level of GHG and reflects the stabilization effort of the GHGs. We in particular will use the parameter ξ to characterize the target carbon budgets of ACs and DCs. The parameter ψ is the fraction of GHG not absorbed by the ocean with $0 < \psi < 1$.[22] The speed of the discovery of new fossil energy is impacted by the parameter α.

Our dynamic decision problem (2)–(6) will be solved in the next section using NPMC with different initial conditions, chosen parameters indicating different scenarios and functions involved reflecting ACs and DCs.

5. Solutions and optimal paths for two model variants

We present numerical solutions for our two model variants using NMPC with different initial conditions of four state variables, K_0, R_0, $y_0$and D_0, indicating different states of economies and environment. In the generic NMPC setting, we use the parameters: $\theta = 0.03$, $\nu = 1.0$, $D^* = 1.0$, $\delta = 0.05$, $\phi = 4$, $\alpha = 8$, $R^0 = 6$, $R^z = 3$, $\rho = 0.05$, and $\psi = 0.5$.[23]

However, as discussed earlier, in the context of the GHG emissions targets, the variation of ξ is important: DCs need to be allowed higher carbon goals (ξD* with higher ξ) than ACs (lower ξ), since DCs have started major industrialization later with their significant GHGs emissions compared to ACs. Moreover, as argued in the CPLC Report (2017), DCs need to obtain some greater share of carbon tax revenue (or other finance, e.g., bonds) recycled to them, in order to control their ξD* to achieve their emission targets. Thus, in our simulations, we assume two types of countries, ACs and DCs, which each need to achieve different GHG emissions targets, ξD*, and that is what ξ expresses. In this context, in reference to these two regions, we also can interpret the effects of the other parameters, E_2, α, ψ, and the initial conditions presumed.

Key features of our numerical study are summarized in Table 1, which provides details on the scenarios shown in Fig. 3 through Fig. 9. Table 1 shows different initial conditions of the state variables, target carbon budgets for the DC and AC, the efficiency index value of fossil fuel, GHG not absorbed by ocean, and other parameter values.

At first, let us discuss some overall trends and generic results. Optimal paths for state variables are shown in Figs. 3–9 for the case of different levels of initially available reserves of fossil fuel and initial condition of other variables. In these figures, we denote: $x_1 = K$ (pink solid line), $x_2 = R$ (red dashed line), $x_3 = D$ (black dash-dot line), $x_4 = y$ (blue dot line). Our results indicate that the capital stock used for renewable energy, in almost all simulations, shows an increasing trend, with a large rise at the beginning followed by a modest growth later (see Figs. 3–9). As observed, a high capital stock is needed during the initial period when the large stock of fossil fuel generates high negative externalities and the

[20] For more detailed explanation and derivation, see Nyambuu and Semmler (2014).

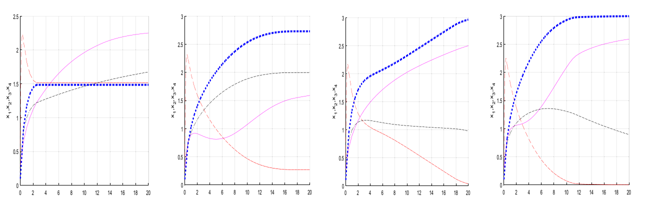
[21] For a detailed justification of the use of this type of welfare function, see Greiner (2011) and Greiner et al. (2014).

[22] For details, see Greiner et al. (2014).

[23] Parameter values follow Greiner et al. (2014) and Nyambuu and Semmler (2014).

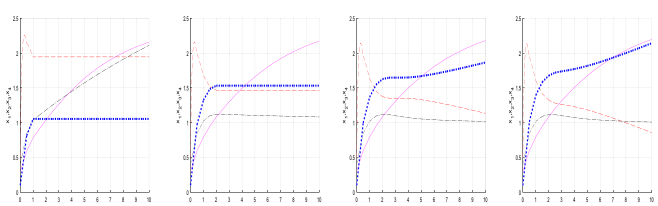
Table 1
Assumptions and parameter values of constructed scenarios.

Fig	State variables' Initial Conditions	Target carbon budgets	Efficiency index	GHG not absorbed by ocean	Effect of fossil fuel discovery	Other parameter values
3	$K_0 = 0.3,\ R_0 = 0.5,\ D_0 = 0.4,\ y_0 = 0.1$	DC ($\xi = 2$), AC ($\xi = 0.2$)	$E_2 = 2,\ E_2 = 10,\ (E_1 = 1)$	$\psi = 0.5$	$\alpha = 8$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$
4	$K_0 = 0.3,\ R_0 = 0.5,\ D_0 = 0.4,\ y_0 = 0.1$	DC ($\xi = 4$), AC ($\xi = 1$; $\xi = 0.5$; $\xi = 0.2$)	$E_2 = 1,\ (E_1 = 1)$	$\psi = 0.5$	$\alpha = 8$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$
5	$K_0 = 0.3,\ R_0 = 0.5,\ y_0 = 0.1,\ D_0 = 0.01;\ D_0 = 0.3;\ D_0 = 0.4;\ D_0 = 1$	DC ($\xi = 2$)	$E_2 = 1,\ (E_1 = 1)$	$\psi = 0.5$	$\alpha = 8$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$
6	$K_0 = 0.3,\ R_0 = 0.5,\ D_0 = 0.4,\ y_0 = 0.1$	DC ($\xi = 2$), AC ($\xi = 0.2$)	$E_2 = 2,\ E_2 = 10,\ (E_1 = 1)$	$\psi = 0.05$	$\alpha = 8$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$
7	$K_0 = 0.3,\ R_0 = 0.5,\ D_0 = 0.4,\ y_0 = 0.1$	DC ($\xi = 4$), AC ($\xi = 1$; $\xi = 0.5$; $\xi = 0.2$)	$E_2 = 1,\ (E_1 = 1)$	$\psi = 0.05$	$\alpha = 8$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$
8	$K_0 = 0.3,\ R_0 = 0.5,\ D_0 = 0.4,\ y_0 = 0.1$	DC ($\xi = 2$), AC ($\xi = 0.2$)	$E_2 = 2,\ E_2 = 10,\ (E_1 = 1)$	$\psi = 0.5$	$\alpha = 0.09$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$
9	$K_0 = 0.3,\ R_0 = 0.5,\ D_0 = 0.4,\ y_0 = 0.1$	DC ($\xi = 2$), AC ($\xi = 0.2$)	$E_2 = 2,\ E_2 = 10,\ (E_1 = 1)$	$\psi = 0.05$	$\alpha = 0.09$	$\theta = 0.03,\ \nu = 1,\ D^* = 1,\ \delta = 0.05,\ \phi = 4,\ R^0 = 6,\ R^z = 3,\ \rho = 0.05$



A. DC (ξ=2), E_2=2 B. DC (ξ=2), E_2=10 C. AC (ξ=0.2), E_2=2 D. AC (ξ=0.2), E_2=10

Fig. 3. Results for DC and AC when $E_2 > 1$. This figure shows dynamic paths for capital (K) using x_1 (pink solid line), stock of fossil fuel (R) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (D) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (y) using x_4 (blue dot line). Results corresponding to different ξ characterizing the target carbon budgets for the DC ($\xi = 2$) and AC ($\xi = 0.2$) are shown over time (t). The efficiency index of fossil fuel (E_2) takes values of $E_2 = 2$, $E_2 = 10$.



a. DC (ξ=4) b. AC (ξ=1) c. AC (ξ=0.5) d. AC (ξ=0.2)

Fig. 4. Results for DC and AC when $E_2 = 1$. This figure shows dynamic paths for capital (K) using x_1 (pink solid line), stock of fossil fuel (R) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (D) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (y) using x_4 (blue dot line). Results corresponding to different ξ characterizing the target carbon budgets for the DC ($\xi = 4$) and AC ($\xi = 1$, $\xi = 0.5$, $\xi = 0.2$) are shown over time (t). The efficiency index of fossil fuel (E_2) takes a value of $E_2 = 1$ in all cases.

corresponding damages.

The effect of damages resulting from the changes in the CO_2 emissions (cumulative) shows a significant initial increase due to the considerable extraction of fossil fuel. But over time, we observe two trends: the emissions increase, but at much slower rate; or the emissions start declining at a very slow rate.

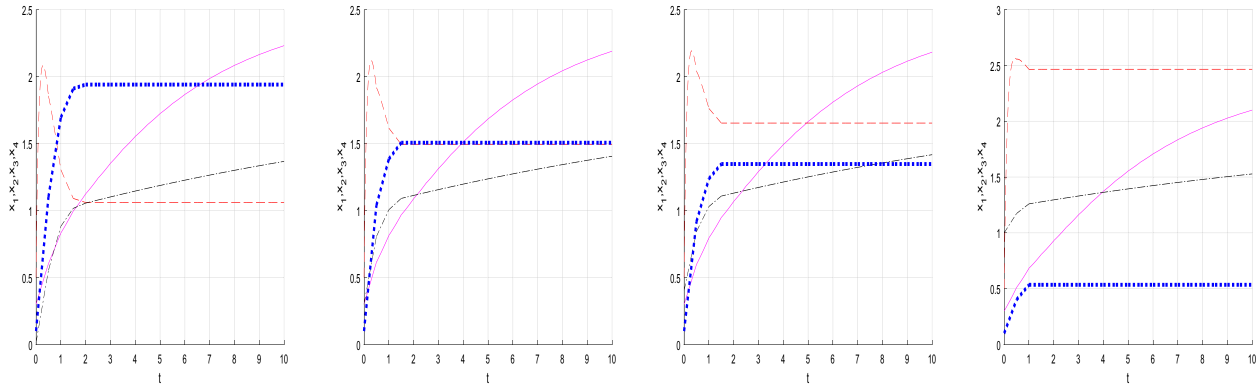
As for the stock of fossil fuel, it increases quickly initially, following the high extraction rate, but it starts declining in a later period. In most cases of the simulations, we observe that the stock of fossil fuel reaches a lower level (with some un-extracted stock left in the ground) when the accumulated past fossil fuel stops rising and reaches a certain level. As a result, growth rates of capital stock used for the production of renewable energy as well as changes in cumulative emissions slow down significantly.

Our results show that the capital stock used for renewable energy increases sharply at first, but its growth rate slows down as time goes by. Since the growth rate of fossil fuel extraction is high during the initial period, a very large capital stock is needed for the usage of renewable energy. Due to extensive extraction of fossil fuel, cumulative CO_2 emissions increase over time. But in the long run, the growth rate of emissions slows down as the stock of fossil fuel declines and reaches a certain level (with some un-extracted stock left in the ground) with convergence in its accumulated past extraction as well. This could happen with no further extraction of fossil fuel, but with an increasing usage of renewable energy sources.

Next, let us look at the specific results for ACs and DCs. Depending on the parameter values corresponding to the GHG emissions target, we can now present and analyze the results for two types of countries comparing ACs and DCs. This is primarily shown using the different emissions targets each needs to achieve; as discussed previously, higher targets for DCs and lower targets for ACs. This distinction is made by using the parameter value of ξ that is applied to the pre-industrial level of cumulative CO_2 emission caused by fossil fuel (D^*).

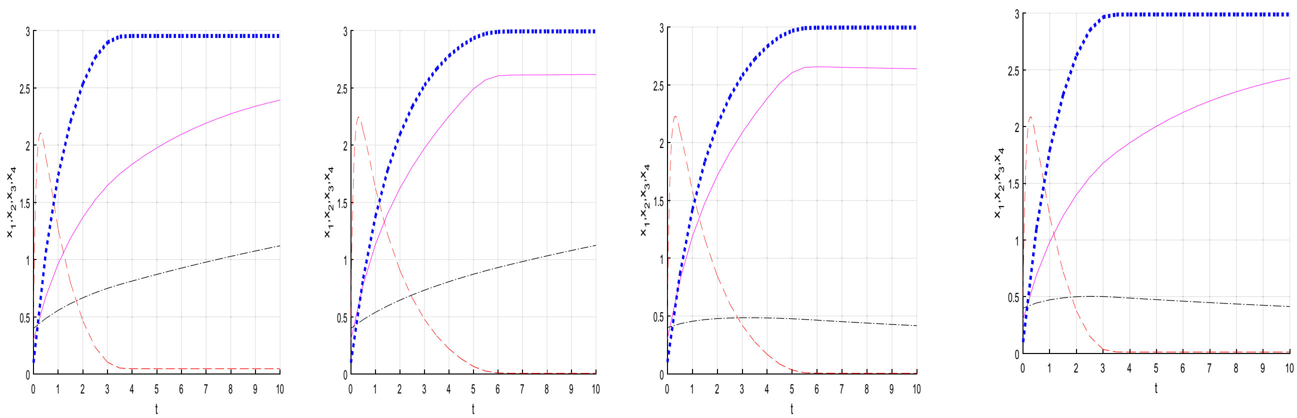
In Fig. 3 we present the optimal paths for the state variables comparing DCs and ACs that respond to the efficiency index of fossil fuel (E_2) being greater than 1 (but with $E_1 = 1$). In these simulations, we have adopted the initial values of the state variables, $K_0 = 0.3$, $R_0 = 0.5$, $D_0 = 0.4$, $y_0 = 0.1$, and $\alpha = 8$, $\psi = 0.5$. For DCs (with $\xi = 2.0$), emissions rise sharply first and still continue rising (Fig. 3a and b). In contrast, for ACs (with $\xi = 0.2$), emissions rise first, but start declining (Fig. 3c and d). However, when E_2 is low ($E_2 = 2$), emissions in DCs rise to a lower level than the results when E_2 is high ($E_2 = 10$) (see Fig. 3a). This slow rise in emissions is associated with cumulative past fossil fuel extraction that stopped rising indicating the amount of fossil fuel that is left under the ground un-extracted. As for ACs, lower E_2 leads to a decline in emissions, but at slower rate (Fig. 3c). Overall, the target levels for DCs and ACs matter.

We further analyze the effects of different emissions target levels characterizing types of AC and DC. Fig. 4 shows the optimal paths for the state variables corresponding to $E_2 = 1$, $E_1 = 1$ and different values of ξ. In these simulations, we have adopted the same initial values of the state variables ($K_0 = 0.3$, $R_0 = 0.5$, $D_0 = 0.4$, $y_0 = 0.1$, $\alpha = 8$, and $\psi = 0.5$) as in the previous case. As the values of ξ decline, the emissions show a decreasing path. We observe that when the fossil fuel extraction declines and stops changing with large amount left in the ground, pollution starts falling in ACs.



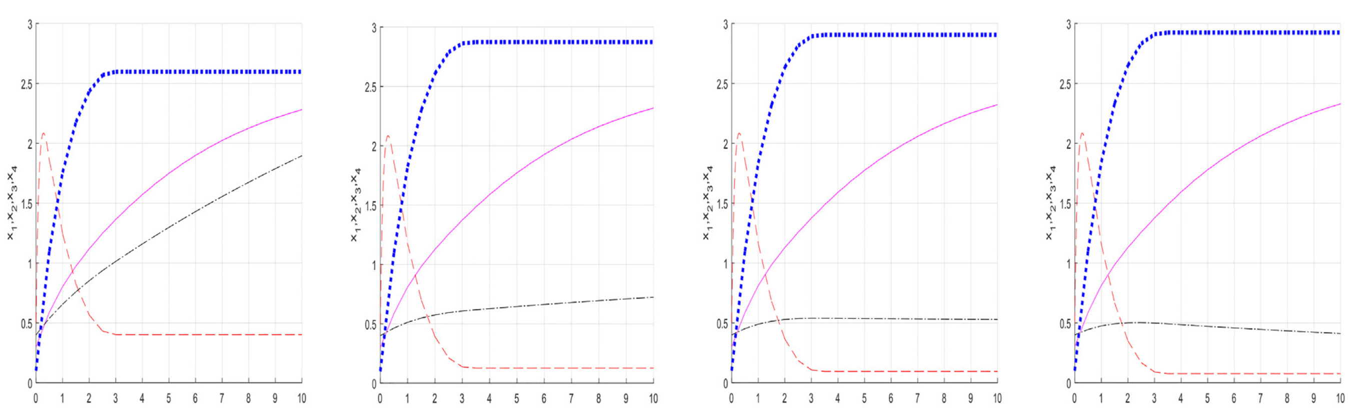
a. D_0=0.01 b.D_0=0.3 c. D_0=0.4 d. D_0=1.0

Fig. 5. Results for DC - Different Initial Conditions for Emissions. This figure shows dynamic paths for capital (*K*) using x_1 (pink solid line), stock of fossil fuel (*R*) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (*D*) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (*y*) using x_4 (blue dot line). Results for the DCs corresponding to different initial condition of emissions ($D_0 = 0.01$, $D_0 = 0.3$, $D_0 = 0.4$, $D_0 = 1.0$) are shown over time (*t*).



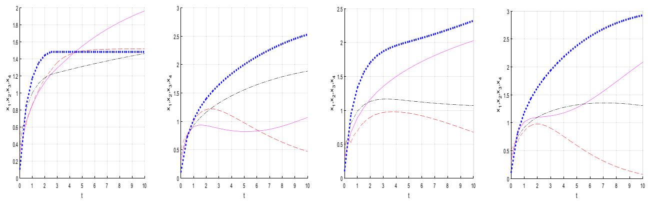
a. DC (ξ=2), E_2=2 b. DC (ξ=2), E_2=10 c. AC (ξ=0.2), E_2=2 d. AC (ξ=0.2), E_2=10

Fig. 6. Results for DC and AC when $\psi = 0.05$, $E_2 > 1$. This figure shows the impact of the fraction of GHG not absorbed by the ocean (ψ) on optimal paths for the variables when the efficiency index of fossil fuel (E_2) takes values of $E_2 = 2$, $E_2 = 10$. Dynamic paths for capital (*K*) using x_1 (pink solid line), stock of fossil fuel (*R*) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (*D*) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (*y*) using x_4 (blue dot line) are illustrated. Results corresponding to different ξ, each characterizing the target carbon budgets for the DC ($\xi = 2$) and AC ($\xi = 0.2$), are shown over time (*t*).



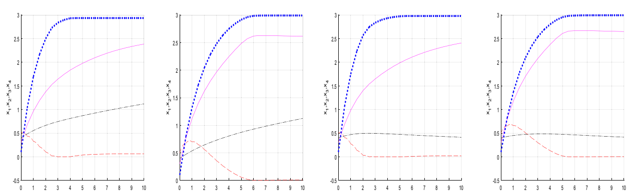
a. DC (ξ=4) b. AC (ξ=1) c. AC (ξ=0.5) d. AC (ξ=0.2)

Fig. 7. Results for DC and AC when $\psi = 0.05$, $E_2 = 1$. This figure shows the impact of the fraction of GHG not absorbed by the ocean (ψ) on optimal paths for the variables when the efficiency index of fossil fuel is $E_2 = 1$. Dynamic paths for capital (*K*) using x_1 (pink solid line), stock of fossil fuel (*R*) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (*D*) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (*y*) using x_4 (blue dot line) are illustrated. Results corresponding to different ξ characterizing the target carbon budgets for the DC ($\xi = 4$) and AC ($\xi = 1$, $\xi = 0.5$, $\xi = 0.2$) are shown over time (*t*).



a. DC (ξ=2), E_2=2 b. DC (ξ=2), E_2=10 c. AC (ξ=0.2), E_2=2 d. AC (ξ=0.2), E_2=10

Fig. 8. Results for DC and AC when $\alpha = 0.09$, $\psi = 0.5$, $E_2 > 1$. In this figure, the impact of fossil fuel discovery (α) on optimal paths for the state variables are shown when the fraction of GHG not absorbed by the ocean is $\psi = 0.5$ and the efficiency index of fossil fuel is $E_2 = 2$ or $E_2 = 10$. Dynamic paths for capital (*K*) using x_1 (pink solid line), stock of fossil fuel (*R*) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (*D*) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (*y*) using x_4 (blue dot line) are illustrated. Results corresponding to different ξ characterizing the target carbon budgets for the DC ($\xi = 2$) and AC ($\xi = 0.2$) are shown over time (*t*).



a. DC (ξ=2), E_2=2 b. DC (ξ=2), E_2=10 c. AC (ξ=0.2), E_2=2 d. AC (ξ=0.2), E_2=10

Fig. 9. Results for DC and AC when $\alpha = 0.09$, $\psi = 0.05$, $E_2 > 1$. In this figure, the impact of fossil fuel discovery (α) on optimal paths for the state variables are shown when the fraction of GHG not absorbed by the ocean is $\psi = 0.05$ and the efficiency index of fossil fuel is $E_2 = 2$ or $E_2 = 10$. Dynamic paths for capital (*K*) using x_1 (pink solid line), stock of fossil fuel (*R*) using x_2 (red dashed line), damages resulting from GHG emissions (cumulative) (*D*) using x_3 (black dash-dot line), and accumulated fossil fuel extraction in the past (*y*) using x_4 (blue dot line) are illustrated. Results corresponding to different ξ characterizing the target carbon budgets for the DC ($\xi = 2$) and AC ($\xi = 0.2$) are shown over time (*t*).

Next, we examine the impact of the initial value of the cumulative emissions (D_0) for DCs, as shown in Fig. 5. The values of other state variables remain the same ($K_0 = 0.3$, $R_0 = 0.5$, $y_0 = 0.1$), but we use $E_1 = 1$, $E_2 = 1$, $\xi = 2$, $\alpha = 8$, $\psi = 0.5$ in each case. When D_0 is very low ($D_0 = 0.01$), accumulated past fossil fuel stock is above the stock of fossil fuel ($y > R$). Because of high rate of extraction of fossil fuel and that which has already accumulated, initially emissions quickly rise. An increase in D_0 reduces the gap until it reaches $y = R$, but eventually their relative positions reverse, yielding $y < R$. This might reflect the initial conditions, i.e., how pollution can affect the decision on how much of fossil fuel should be extracted or left un-extracted in the ground. For example, when the initial pollution level is very low, as in Fig. 5a, a lot of fossil fuel is extracted, and a certain level of fossil fuel is left in the ground. However, when the initial pollution level is very high, as in Fig. 5d, the potential hazard of the pollution is realized and extraction ceases, thus leaving large amount of fossil fuel in the ground. Our results indicate that the higher the initial emissions, the higher the accumulated emissions.

Furthermore, we investigate the response of the emissions to changes in the fraction of GHG not absorbed by the ocean (ψ). The same condition as in Fig. 3 ($K_0 = 0.3$, $R_0 = 0.5$, $D_0 = 0.4$, $y_0 = 0.1$, $E_1 = 1$, $E_2 > 1$, $\alpha = 8$) was applied, but with lower parameter value of ψ (from 0.5 to 0.05). In Fig. 6, we observe that lower level of this parameter results in much lower level of accumulated pollution compared to the results shown in Fig. 3. To investigate the effect of this parameter when $E_2 = 1$, we use the same condition as in Fig. 4 ($K_0 = 0.3$, $R_0 = 0.5$, $D_0 = 0.4$, $y_0 = 0.1$, $E_1 = 1$, $E_2 = 1$, $\alpha = 8$), but with lower $\psi = 0.05$. As shown in Fig. 7, there are lower accumulated emissions than in the results presented in Fig. 4.

In the final scenarios, we assess the effect of fossil fuel discovery due to changes in the parameter α. This is the same condition as in Fig. 3 ($K_0 = 0.3$, $R_0 = 0.5$, $D_0 = 0.4$, $y_0 = 0.1$, $E_1 = 1$, $E_2 > 1$), but a much lower parameter value of α (=0.09), is used for the simulations; these are shown in Fig. 8. We observe similar patterns for the emissions, namely a continuously increasing trend for DCs and an initial rise with a decline for ACs as in Fig. 3, but with slightly different level. As expected, fossil fuel discovery directly affects the stock of fossil fuel and past accumulated fossil fuel; lower values of α lead to lower stocks of fossil fuel as shown in Fig. 8.

Similarly, for Fig. 9, we used the condition as in Fig. 8, but with lower ψ (=0.05) that results in much lower emissions. Most importantly, for both DCs and ACs, these outcomes are obtained when fossil fuel is not extracted and left in the ground as illustrated in Fig. 9.

Overall, based on different scenarios for DCs and ACs that examined the effects of the underlying variants of the model, we suggest that a slow-down or gradual reduction in CO_2 emissions is possible. As we have shown, discovery and extraction rates of fossil fuel along with GHG emission target levels play an important role in emission controls. In addition, the efficiency of fossil fuel as well as the unabsorbed GHG of the ocean, can affect the trajectories of cumulative emissions over time.

6. Conclusion

In its 2018 report, the International Panel on Climate Change (IPCC) (2018) demonstrated that a higher probability of limiting global warming to 1.5 °C (instead of 2 °C) would only be obtained if the net reduction in CO_2 emissions from 2020 to 2040 was reduced to zero. The United Nations Environment Program (UNEP) (2018) addresses this issue of the emissions gap as well. To achieve such an ambitious goal, it is essential to reduce or simply phase out coal production and consumption entirely, as international studies have recently shown (see Sartor, 2018). In this context, we have developed different model constellations illustrating some fair burden sharing between advanced countries and developing countries: both country groups need to reduce coal production and consumption, yet each might have different targets when the overall CO_2 is brought down. We acknowledge that technological transfer of more efficient green technology to developing countries should be expedited, which would clearly help reduce CO_2 emission. In a recent contribution, Popp (2015) has convincingly demonstrated how to achieve this.

Coal generates great externalities, while also allowing high CO_2 emission as compared to other types of fossil fuel. As estimated by climate scientists, coal use appears as a significant source of global warming and a major driver pushing us past the carbon budget threshold. The price of coal, as is currently supplied, does not reflect these facts; in many countries, the price of carbon does not include the cost of the externalities it generates – however, other traditional fossil fuel energy sources do not usually incorporate it either. Though the energy technology is rapidly changing the efficiency in the production and use of fossil fuels, making certain products more environmentally friendly than in the past, the decarbonization procedures do not seem to be sufficiently developed to have significant scale effects in reducing CO_2. On the other hand, new technologies, e.g., edge computing, genetic engineering, and big data analytics, may prove beneficial, bringing about improvements to the traditional procedures. Yet, overall effects are hard to predict as new technologies may also have unexpected consequences.

The consequences of past pollution may remain with us for a while. For a more extensive discussion of the co-damages of fossil fuel use – or co-benefits when reduced – see the IMF study by Parry et al. (2014), where a country-by-country analysis is undertaken. Predicted damages and disasters worldwide and for the US economy due to climate change are addressed in Mittnik et al. (2018) and USGCRP (2017).

Because of the current insufficiency in the pricing of long-run externalities of fossil fuel energy, and the need for expedited actions, researchers suggest that a scale-up of renewable energy use, together with

additional investment in green capital supporting renewable energy production, is needed. This is also proposed by the Carbon Pricing Leadership Coalition (CPLC) (2017) that promotes the idea that revenues from a carbon tax as well as new forms of finance, such as green bond issuance, are used to expand renewable energy capacity. Such a policy is also in line with EU efforts, see for example the European Commission (2017) report that pushes for scaling up of finance of renewable energy through securitizations and easier bank credit.[24]

A more global political initiative supporting the above mentioned efforts is represented by the recently developed United Nations Sustainable Development Goals (SDG); in particular by goal 13. This is focused on climate change and deals with the required efforts and policies needed to limit global temperature increases to 1.5 °C as compared to the end of the 19th century. Such efforts are necessary to avoid increasingly frequent and severe climate-related disasters.

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